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DEPOSITION AND STORAGE OF FINE-GRAINED SEDIMENT WITHIN THE MAIN CHANNEL SYSTEM OF THE RIVER TWEED, SCOTLAND

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ABSTRACT

This paper assesses the importance of deposition and storage of fine-grained (*c.* $< 150\ \mu$m) sediment on the floodplains and beds of the main (non-tidal) channels of the River Tweed (4390 km^2), Scotland, and two of its tributaries (River Teviot and Ettrick Water). Caesium-137 analysis of floodplain sediment cores has been used to estimate average rates of overbank sedimentation during the last 30 to 40 years. Average values for individual transects ranged from 0·16 to 2·18 kg m^{-2} a^{-1} (0·13 to 2·2 mm a^{-1}). The mean for the 10 transects investigated was 1·29 kg m^{-2} a^{-1} (1·3 mm a^{-1}). The total amount of fine sediment deposited was estimated to be about 44 000 t a^{-1}. The fine-grained sediment stored in the channel bed was quantified using resuspension techniques. Average values for individual sites ranged from 0·12 to 0·96 kg m^{-2}. The mean for the 10 sites investigated was 0·56 kg m^{-2}. The total amount of sediment stored on the channel bed of the main channel system at the time of sampling was estimated to be about 4300 t. Comparison of these estimates of floodplain and channel storage with the estimated suspended sediment load for the River Tweed at the downstream gauging site at Norham, indicates that floodplain sedimentation and channel bed storage represent about 40 and 4 per cent, respectively, of the annual load of fine sediment delivered to the main channel system. Erosion of channel banks will reintroduce the equivalent of about 30 per cent of the floodplain-deposited sediment back into the channel. The residence time of the fine-grained sediment stored on the channel bed is probably less than one year, but that of sediment deposited on the floodplain is likely to be considerably longer. Conveyance losses associated with overbank deposition have important implications for the routing of sediment through fluvial systems and the interpretation of downstream sediment yields. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: sediment storage; sediment budget; conveyance loss; floodplain sedimentation; channel bed sediment; caesium-137; River Tweed

INTRODUCTION

Deposition of fine-grained sediment on floodplains during overbank events (Figure 1) and within channels represents an important component of the fluvial suspended sediment budget of many river basins (Meade *et al.*, 1990; Phillips, 1991; Meade, 1994; Mertes, 1994) and contributes to the often cited discrepancy between upstream erosion rates and downstream sediment yields (Trimble, 1977; Meade 1982; Walling, 1983). The suspended sediment flux at the outlet of a drainage basin will commonly represent only a proportion of the fine-grained sediment delivered to the channel system. Campo and Desloges (1994), for example, estimated that approximately 10 per cent of the long-term annual sediment yield from the 561 km^2 basin of the Saugeen River in Ontario, Canada, was deposited on its floodplain. Similarly, Middelkoop and Asselman (1994) combined an assessment of the mass of fine-grained sediment deposited along a 100 km reach of the floodplain of the River Waal in the Netherlands, during a 40-year flood occurring between December 1993 and January 1994, with information on the suspended sediment load of the river, to estimate that about 19 per cent of the total suspended sediment load transported into the reach during the event was deposited on the floodplain. In the UK, previous studies by the authors have shown that >20 per cent of the sediment delivered

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Figure 1. Overbank flooding in the lower reaches of the River Tweed near the tidal limit at Norham (see Figure 2 for location) in April 1992. The channel is located just in front of the hut and is approximately 90 m wide at this point. The floodplain along this reach is several hundred metres wide. The photograph is oriented upstream and was taken by a local resident

to the main channel system may be deposited on the floodplains bordering these systems (Lambert and Walling, 1987; Walling and Quine, 1993; Owens *et al.*, 1997; Walling *et al.*, 1998a).

Quantification of these conveyance losses is, in consequence, an essential component in studies concerned with monitoring and modelling the routing and export of sediment from drainage basins or smaller landscape units (e.g. channel reaches) (Swanson *et al.*, 1982). Not only is information required on the magnitude of conveyance losses within the basin, but consideration must also be given to the residence times associated with individual stores (Meade *et al.*, 1990). In some instances sediment storage may involve annual, or longer, timescales, while in others storage may be short-term (i.e. days or months) with no net conveyance loss to the system existing at the annual timescale. An appreciation of the magnitude of fine-grained sediment conveyance loss and storage on floodplains and channel beds is also important for understanding and modelling the delivery and fate of sediment-associated pollutants and contaminants such as heavy metals, radionuclides and synthetic organic compounds (e.g. PCBs) in river systems (Marron, 1992; Rowan and Walling, 1992; Jain and Ram, 1997; Macklin *et al.*, 1997). Thus, for example, in the case of conveyance losses of sediment to floodplains, sediment-associated contaminants may persist in the floodplain sediment for long periods of time, and may be reintroduced into the channel at a later date if the floodplain sediment is subsequently remobilized.

Information on the magnitude of floodplain and channel conveyance losses and the residence times associated with such storage is also needed from a management perspective, in order to implement appropriate strategies for controlling the numerous problems associated with fine sediment transport in river systems. Many of these problems are related to pollution control and siltation of channels and receiving water bodies. Thus, increases in the storage of fine-grained sediment within gravel-bed rivers have been shown to have deleterious effects on salmonid spawning, and the number and diversity of benthic invertebrates (Scullion, 1983; Sear, 1993). Problems associated with the deposition and storage of fine-grained sediment within channels and on floodplains can be exacerbated by increases in the input of fine sediment to the fluvial system associated with the upstream impact of forestry and other land-use activities (cf. Maitland *et al.*, 1994; Leeks and Marks, 1997; Marks and Rutt, 1997).

There have been very few studies, especially in the UK, which have examined conveyance losses of fine-grained sediment within drainage basins >1000 km^2, and which have placed the results within the context of the sediment yield at the basin outlet. This paper presents estimates of contemporary floodplain conveyance loss and channel bed storage of fine-grained ($c.$ <150 μm) sediment for the main (non-tidal) channel system

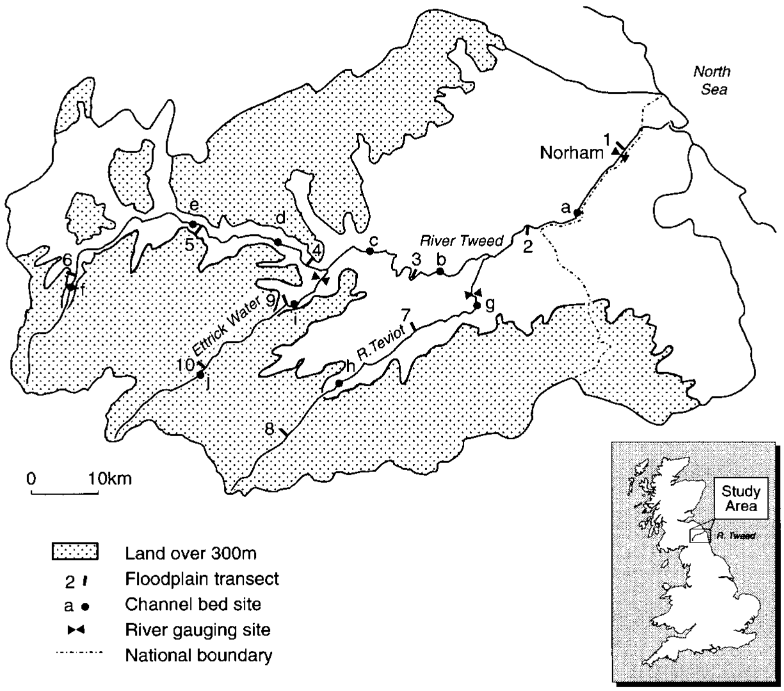

Figure 2. Location map showing the River Tweed basin, floodplain transects, channel bed sampling sites and river gauging sites

of the River Tweed (4390 km^2), in the Borders region of Scotland. Attention has been directed primarily towards the main channel of the River Tweed, but the principal channels of two of its main tributaries, the River Teviot and the Ettrick Water, have also been considered, to provide a more realistic estimate of overall conveyance losses in the basin. To establish the significance of these results with respect to the overall suspended sediment budget of the study catchment, estimates of storage and conveyance loss have been compared to the suspended sediment yield at the catchment outlet. To the authors' knowledge, the present study represents the first attempt to quantify contemporary conveyance losses and storage of fine-grained sediment in a major river system in Scotland.

This study forms part of a larger project (cf. Walling *et al.*, 1998a,b, 1999) within the Land–Ocean Interaction Study (LOIS) funded by the UK Natural Environment Research Council. The LOIS programme is concerned with the monitoring and modelling of material fluxes from the land to the oceans for parts of the UK (Wilkinson *et al.*, 1997), and one of the aims of the present project was to quantify the influence of floodplain and channel conveyance losses and storage on suspended sediment fluxes from the study rivers. The results of a similar investigation undertaken on the River Ouse in Yorkshire are presented in Walling *et al.* (1998a).

STUDY AREA AND METHODS

Study area

Most of the River Tweed basin is located in the Borders region of Scotland, but the southeastern portion of the basin is located in Northumbria, England. The Tweed basin is the second largest in Scotland, with a catchment area of about 4390 km^2 above the tidal limit at Norham (Figure 2). The catchment area of the River Teviot above the Scottish Environment Protection Agency gauging site at Ormiston (National Grid Reference (NGR) NT702280) is about 1110 km^2, while that of Ettrick Water above the gauging site at Lindean (NGR

NT486315) is about 500 km^2. For most of its length, the River Tweed is an unpolluted, gravel-bed river (cf. Robson and Neal, 1997; Neal *et al.*, 1997), and it flows west to east for approximately 160 km from its headwaters to the North Sea. The mean discharge and mean annual flood (1959–1995) for the River Tweed at Norham are 77·8 and 837 $m^3 s^{-1}$, respectively. The mean discharges for the River Teviot at Ormiston (1960–1995) and Ettrick Water at Lindean (1961–1995) are 19·6 and 14·9 $m^3 s^{-1}$, respectively (Fox and Johnson, 1997). Suspended sediment concentrations are typically <10 mg l^{-1} during baseflow, but concentrations may exceed 500 mg l^{-1} during high discharges associated with storm events (unpublished data; Neal *et al.*, 1997). (Available data on annual suspended sediment loads are presented in Table III.)

The Tweed basin is largely rural with a population density of 22 persons km^{-2} (Robson and Neal, 1997) and there are no major urban centres. About 55 per cent of the basin lies above 300 m a.s.l. (Figure 2) and altitude locally exceeds 800 m in the headwaters. In the eastern area of the basin, most of the land is low-lying and generally flat, except for the Cheviot Hills to the south. The underlying geology is dominated by Ordovician and Silurian greywackes, slates and shales in the west and north of the basin, with a mixture of Devonian sandstones and Carboniferous limestones in the east. There are also igneous intrusive (granite) and extrusive (basic lavas) rocks of Devonian age in the southeast of the basin in the Cheviot Hills. The soils include well drained brown earths (lowlands), gleys (intermediate slopes), and podzols and peats (uplands). Land use is closely related to altitude, relief and underlying geology, and varies from moorland and rough grazing in the upland areas to cultivated land (mainly for cereal crops) in the lowlands. Approximately 16 per cent of the basin is forested, predominantly with conifer plantations. The climate is cool-temperate, with average monthly temperatures ranging from 1°C in January to 13°C in August. The average annual rainfall (1961–1990) for the basin is 969 mm, although locally rainfall ranges from >2000 mm in the uplands to <700 mm in the lowlands to the east (Fox and Johnson, 1997).

Methods

Rates of overbank floodplain sedimentation and the associated sediment storage were estimated using fallout caesium-137 (^{137}Cs) measurements. The ^{137}Cs approach is founded on the fact that ^{137}Cs fallout has been characterized by a well defined temporal pattern (fallout commenced in the early 1950s with a peak in fallout in 1963) which can be used to establish a chronology for the sediment profile. In addition, the total ^{137}Cs inventory for a sediment core can be partitioned into two components representing, firstly, the local atmospheric fallout (which can be determined by sampling adjacent sites above the level of flood inundation) and, secondly, the deposition of sediment-associated ^{137}Cs during periods of overbank flows (see also He and Walling, 1996a; Walling and He, 1997a, 1998). The magnitude of the latter component will directly reflect the amount of sedimentation during the period since the onset of ^{137}Cs fallout, and can be used to estimate the sedimentation rate. As the samples analysed in this study were collected in 1995, the sedimentation rates presented below represent average values for the last 32 or 41 years, depending on whether the 1963 ^{137}Cs fallout peak or the onset of ^{137}Cs fallout in 1954, respectively, was used as the basis for the chronology. At each of 10 floodplain sites (Figure 2), between five and 11 sediment cores were collected to depths of about 0·6 m (reconnaissance coring suggested that ^{137}Cs was unlikely to extend below 0·5 m depth) along a transect perpendicular to the channel. Transect lengths ranged between 58 and 279 m, depending on the nature and extent of the floodplain. The 10 sites were chosen at approximately equidistant locations along the lengths of the main channels, in an attempt to provide representative estimates of overbank sedimentation rates along the entire length of the study rivers. Thus, in the case of the main channel of the River Tweed, the distance between adjacent sites was approximately 25 km, although there were some sites where this distance varied in response to local factors (i.e. the absence of a suitable floodplain, the location of towns, problems of access etc.). The sites were also selected to be representative of the floodplain within particular reaches of the study rivers, with reaches being defined, for example, by the location of tributary rivers, and river and valley topography. Hence, site 3 (Figure 2) on the River Tweed was chosen to lie approximately midway along the reach extending between the tributary confluences of the Ettrick Water and the River Teviot. It must be recognized, however, that overbank sedimentation on floodplains is spatially variable (cf. Middelkoop and Asselman, 1998; Walling and He, 1998) and that any attempt to represent the sedimentation rates within a reach using a single transect necessarily introduces uncertainty in the resulting estimates. However, such

problems are encountered in most field studies that attempt to sample spatially heterogeneous phenomena, particularly in large drainage basins (i.e. >4000 km^2), and an attempt (which is described later) has been made to limit the uncertainty associated with unrepresentative values.

For each of the 10 transects, most of the sediment cores were analysed as bulk samples, but one core (usually one of the cores located near to the channel) was sectioned into 10 mm increments to determine the depth distribution of ^{137}Cs, and hence the sedimentation rate, at that sampling point. This value was then used to estimate the sedimentation rates for the other (bulk) cores in the transect, from their excess ^{137}Cs inventory relative to the local ^{137}Cs fallout (reference) inventory and the specific surface area of the deposited sediment (which reflects its grain size distribution). The procedure employed is explained in detail later in this paper. The local reference inventory for each transect was estimated by collecting several (usually five or more) sets of sediment cores from adjacent areas of essentially flat, undisturbed land above the level of flood inundation. Subtraction of the reference inventory value from the total ^{137}Cs inventory for the floodplain core provides a value for the *excess* inventory, which represents an estimate of the ^{137}Cs associated with deposited sediment, and which will in turn reflect the sedimentation rate and the ^{137}Cs content of the deposited sediment. Caesium-137 activities were determined by gamma spectrometry using a HPGe detector. The specific surface area of the mineral fraction of the surface (top 10 mm) sediment at each sampling point was estimated from the absolute grain size distribution, which was measured using a Coulter LS130 laser diffraction granulometer, after removal of organic matter with H_2O_2, and chemical [$(NaPO_3)_6$] and ultrasonic dispersion.

The amount of fine-grained sediment stored on the channel bed of the study rivers was determined using the approach developed by Lambert and Walling (1988). A metal cylinder (surface area = 0·16 m^2, height = 0·8 m) was carefully lowered onto the channel bed, and then rotated and pushed into the bed to create a seal and permit a known area of the bed to be sampled. It is difficult to determine the precise depth to which fine-grained sediment will infiltrate into the bed, and from which it will be subsequently remobilized during high flows. In gravel-bed rivers that exhibit armouring, the depth of infiltration of fines will largely be a function of the grain size composition of the armour layer (i.e. D_{50} or D_{90}) and water depth and velocity, and will thus be temporally and spatially variable. Beschta and Jackson (1979) used results from flume studies to suggest that fine-grained sediment will be remobilized from a depth of about 10 mm, while Frostick *et al.* (1984), Lisle (1989) and Klingeman (1992) (in Diplas and Parker, 1992) found that this depth typically ranged between 50 and 100 mm, although, for high flows capable of mobilizing the armour layer, the depth of remobilization may be > 100 mm and may be equal to >2 D_{50} of the armour layer. The D_{50} of the surface bed material for four reaches along the Rivers Tweed and Teviot ranges from about 40 to 70 mm (Hey and Thorne, 1986). Consequently, in this study, two slightly different procedures were used to manually disturb the bed, in order to provide a measure of the likely range of fine sediment storage. In the first, only the water column contained within the cylinder was agitated, thereby resuspending the fine sediment stored on the bed surface as a drape. In the second approach, a rod was used to disturb approximately the upper 100 mm of the channel bed, thereby resuspending both the surface drape and the sediment stored within the upper 100 mm of the bed matrix. Representative samples of the water and resuspended sediment contained in the cylinder were collected immediately after agitation, using 0·5 1 bottles. The sediment concentrations in the water samples ($C_s(t)$; kg 1^{-1}) were determined by filtration, and the amount of sediment released from the bed per unit surface area ($B_r(t)$; kg m^{-2}) was calculated as:

$$B_r(t) = \frac{C_s(t)W_v(t)}{A} \tag{1}$$

where $W_v(t)$ = volume of water enclosed in the cylinder (1), which is calculated from the depth of water within the cylinder and its surface area (A; m^2).

Channel bed storage was determined at 10 sites in the study area (Figure 2) under low flow conditions when channel bed composition was relatively stable (as recommended by Adams and Beschta (1980)) during the summer of 1996. Initially, the intention was that the location of the bed sampling sites should coincide with the floodplain transect sites. However, in six out of 10 cases this was impossible, due to problems associated with access to the channel, safety and water depth (the cylinder cannot be used in water >0·8 m deep), and

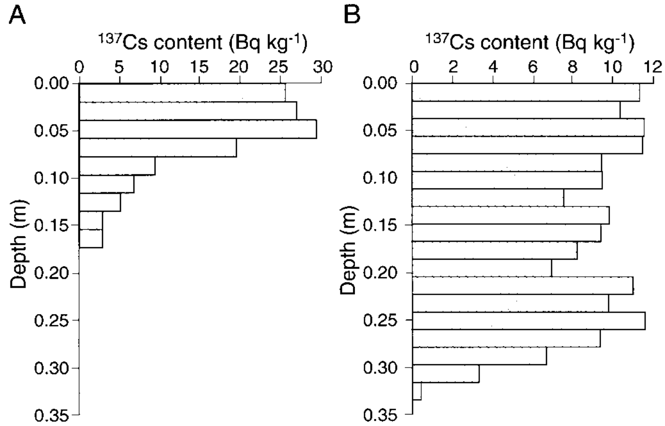

Figure 3. The depth distributions of ^{137}Cs associated with floodplain sediment cores collected from (A) an uncultivated site (site 10) and (B) a cultivated site (site 9) along the Ettrick Water

alternative bed storage sites within each reach were chosen. Each site was chosen to be representative of the bed material within the surrounding reach. As with the floodplain sites, it is important to recognize that the amount of fine-grained sediment storage within the channels of gravel-bed rivers is spatially variable (cf. Adams and Beschta, 1980; Frostick *et al.*, 1984; Lambert and Walling, 1988; Walling and Quine, 1993) and is dependent on many factors, including local bed morphology, texture and structure, channel sinuosity and water depth (cf. Adams and Beschta, 1980; Diplas and Parker, 1992). Consequently, estimates of sediment storage on the channel bed obtained using the procedures outlined above are likely to be sensitive to the precise location of the sampling sites, and, particularly, to the location of the sites relative to the pool and riffle structure of the bed. Therefore, at each site, sediment storage was determined at three locations to take some account of the local spatial variability of storage as a function of varying water depth including, if possible, one pool and one riffle sampling point.

The organic matter content of the resuspended bed sediment was determined using a Carlo-Erba ANA1400 Automated Nitrogen Analyser (which measures organic C and N).

RESULTS

Floodplain sedimentation

Figure 3 illustrates the depth distribution of ^{137}Cs in two sediment cores collected from representative uncultivated and cultivated floodplain sites located along the Ettrick Water. For the core collected from the uncultivated floodplain at site 10, the ^{137}Cs peak is located at 60 mm (56·2 kg m^{-2} accumulated mass) depth, and this can be equated with the ^{137}Cs fallout peak in 1963. To avoid overestimating the sedimentation rate, it is necessary to take account of the slow downward migration of ^{137}Cs (V; kg m^{-2} a^{-1}) in the sediment due to internal soil processes such as bioturbation and leaching (cf. He and Walling, 1996a; Owens *et al.*, 1996). Based on the ^{137}Cs depth distributions for local undisturbed soil profiles located above the level of inundation, the downward migration rate was estimated to be 0·5 kg m^{-2} a^{-1}. On this basis, the average sedimentation rate $R_{ou}(t)$ (kg m^{-2} a^{-1}) can be calculated as:

$$R_{ou}(t) = \left(\frac{M_p(t)}{T_p}\right) - V \tag{2}$$

where $M_p(t)$ = cumulative mass depth of the 1963 ^{137}Cs peak at time t (kg m^{-2}) and T_p = time elapsed

between 1963 and the time t that the core was collected (years). Thus, in the example of the core collected from site 10, the average sedimentation rate between 1963 and 1995 was 1·3 kg m^{-2} a^{-1} (1·4 mm a^{-1}). In the case of the core collected from the cultivated floodplain at site 9, the ^{137}Cs extends in the profile to a depth of 0·34 m. The plough depth for this site is known to be 0·25 m, and the existence of 0·09 m (108 kg m^{-2}) of sediment containing substantial concentrations of ^{137}Cs below the plough depth can be ascribed to progressive overbank deposition. The average sedimentation rate $R_{oc}(t)$ (kg m^{-2} a^{-1}) can be calculated as:

$$R_{oc}(t) = \frac{M_s(t) - M_{pl}(t)}{T_s} \tag{3}$$

where $M_s(t)$ = cumulative mass depth to the base of the ^{137}Cs profile at time t (kg m^{-2}), $M_{pl}(t)$ = cumulative mass depth of the plough layer at time t (kg m^{-2}) and T_s = period elapsed between the commencement of ^{137}Cs fallout and the time t that the core was collected (years). The effect of downward migration of ^{137}Cs can be ignored in a cultivated profile, because the soil is regularly mixed by the ploughing process. Hence, in the example of the core from site 9, the average sedimentation rate during the period between the onset of ^{137}Cs fallout and the time that the core was collected (i.e. 41 years) was 2·6 kg m^{-2} a^{-1} (2·2 mm a^{-1}).

The sedimentation rate determined for the sectioned core collected from each transect was used as a basis for estimating the sedimentation rate for the other bulk cores ($R_i(t)$; kg m^{-2} a^{-1}) in the transect as:

$$R_i(t) = R_o(t)\left(\frac{I_{ei}(t)}{I_{eo}(t)}\right)\left(\frac{S_o}{S_i}\right)^{0.75} \tag{4}$$

where $I_{ei}(t)$ = excess ^{137}Cs inventory at sampling point i at time t (Bq m^{-2}), $I_{eo}(t)$ = excess ^{137}Cs inventory for the sectioned core at t (Bq m^{-2}), S_o = specific surface area of the deposited sediment for the sectioned core (m^2 kg^{-1}) and S_i = specific surface area of the deposited sediment at sampling point i (m^2 kg^{-1}). Well documented relationships exist between the particle size of overbank deposits and distance from the channel (Marriott, 1992; He and Walling, 1998; Walling *et al.*, 1998b) and between particle size and ^{137}Cs concentration (Livens and Baxter, 1988; He and Walling, 1996b). Hence, the ratio S_o/S_i may be used to correct for differences in the particle size composition between the sectioned core and the bulk core. The exponent 0·75 in Equation 4 describes the general relationship between specific surface area and ^{137}Cs concentration (He and Owens, 1995; He and Walling, 1996b).

Figure 4 illustrates the relationship between sedimentation rate and distance from the channel for each of the 10 transects. There is considerable variation in sedimentation rates within and between transects. Generally, rates of overbank sedimentation tend to decrease with increasing distance from the channel (for example at site 7). This finding is consistent with other studies (e.g. Kesel *et al.*, 1974; Walling and He, 1998; Walling *et al.*, 1998a) and is thought to reflect the reduced diffusive transport of suspended sediment, and reduced depth and duration of flood inundation, towards the outer limits of the floodplain. However, at seven out of the 10 sites the distance–sedimentation rate relationship also reflects additional controls. For example, at some sites (such as 2, 4 and 8), although there is a general reduction in sedimentation rate with increasing distance, there is enhanced deposition at the outermost sampling points. This is probably due to the deposition of sediment eroded from adjacent hillslopes. These sampling points were therefore excluded when estimating the average overbank sedimentation rate for each transect. At other sites (such as 3 and 10), deviations from the simple distance–sedimentation rate relationship reflect the effect of drainage ditches in bringing water and sediment from the main channel to distal parts of the floodplain (see also Simm and Walling, 1998). In other cases variations in deposition rate reflect the influence of floodplain topography (such as sites 5, 6, 9 and 10) or, perhaps, soil disturbance by grazing animals (such as site 1).

Estimated sedimentation rates for individual sampling points range from 0 to 7·1 kg m^{-2} a^{-1} (0 to 5·8 mm a^{-1}). Table I lists the estimates of average sedimentation rate (based on all suitable cores) for each transect. Values range from 0·16 kg m^{-2} a^{-1} (0·13 mm a^{-1}) (site 4) to 2·18 kg m^{-2} a^{-1} (2·2 mm a^{-1}) (site 5), and the mean for all 10 sites is 1·29 kg m^{-2} a^{-1} (1·3 mm a^{-1}). This mean sedimentation rate is similar to those documented by the authors for other drainage basins in the UK. Using a similar approach, Walling and He

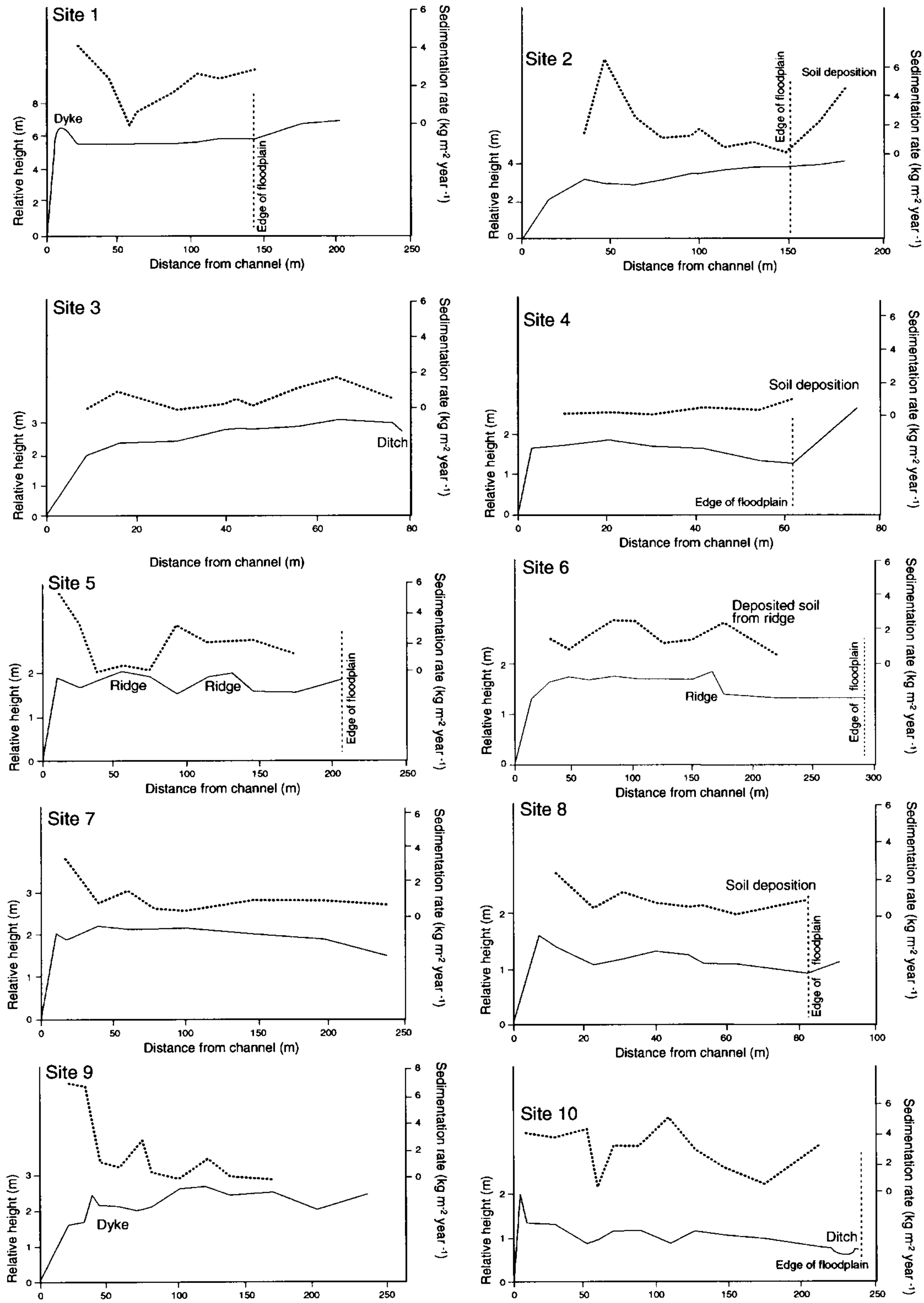

Figure 4. Relationships between overbank sedimentation rate and distance from the channel for the 10 floodplain sampling locations in the Tweed basin

Table I. Average overbank sedimentation rates for the individual floodplain transects and estimates of conveyance loss for each reach and for each river

River	Site	Number of cores	Average sedimentation rate ($kg\ m^{-2}\ a^{-1}$)	Reach	Conveyance loss ($t\ a^{-1}$)
Tweed	1	7	1·26	1 (tidal limit) to 2	4852
	2	9	1·69	2 to 3	2748
	3	9	0·71	3 to 4	844
	4	5	0·16	4 to 5	3538
	5	8	2·18	5 to 6	11 028
	6	9	1·55	6 to source	3457
	Mean		*1·26*	*Total*	*26 467*
Teviot	7	8	1·05	confluence to 7	4983
	8	7	0·75	7 to 8	2424
	Mean		*0·90*	8 to source	195
				Total	*7602*
Ettrick	9	11	1·90	confluence to 9	2793
	10	9	1·63	9 to 10	4588
	Mean		*1·77*	10 to source	2470
				Total	*9851*
All three rivers	***Mean*** ($n = 10$)		***1·29***	***Total***	***43 920***

(1997b) estimated that the mean sedimentation rate for nine transects along an 11 km reach of the River Culm, Devon, was 1·2 $kg\ m^{-2}\ a^{-1}$ (range 0·5 to 3·3 $kg\ m^{-2}\ a^{-1}$), while Walling *et al.* (1998a) found that the mean sedimentation rate for 26 transects located throughout the catchment of the River Ouse, Yorkshire, was 2·06 $kg\ m^{-2}\ a^{-1}$ (range 0·10 to 5·54 $kg\ m^{-2}\ a^{-1}$). For a 14 km reach of the River Stour in Dorset, Walling and He (1997a) estimated a mean sedimentation rate for nine transects of approximately 0·8 $kg\ m^{-2}\ a^{-1}$.

The estimates of average sedimentation rate for each transect were used to calculate the total annual deposition of sediment on the floodplains of the study rivers ($S_f(t)$; $t\ a^{-1}$) as:

$$S_f(t) = \sum_{i=1}^{n} \left(\frac{R_i(t) + R_{i+1}(t)}{2} \right) \left(\frac{L_i + L_{i+1}}{2} \right) Dk \tag{5}$$

where $R_i(t)$ and $R_{i+1}(t)$ = average sedimentation rates for the transects at sites i and $i+1$ (the next site upstream) at time t ($kg\ m^{-2}\ a^{-1}$), L_i and L_{i+1} = lengths of the transect at sites i and $i+1$ (km), D = length of the floodplain between two consecutive transects (km), and k = a dimensionless scaling factor (required to obtain the correct units for $S_f(t)$). At sites where there was evidence of enhanced sediment deposition due to erosion from the adjacent hillslope, values of L were adjusted accordingly. In some instances Equation 5 was modified slightly. For the upstream reach of each of the three rivers it is assumed that R_{i+1} and L_{i+1} (i.e. for the source area) are both 0, while for the downstream reaches of the River Teviot and Ettrick Water, because the first site is not located at the downstream limit of the river, it is assumed that the values of R_i and L_i (i.e. for the downstream site) are the same as those for R_{i+1} and L_{i+1} (i.e. for the first transect upstream).

It is, however, important to recognize that the accuracy of the estimates of total floodplain deposition produced using Equation 5 is heavily dependent on the validity of extrapolating the average values of sedimentation rate obtained for each individual transect to the adjacent floodplain reaches. Table I demonstrates that these values exhibit considerable variation between transects associated with variations in local conditions (such as channel and floodplain geometry, microtopography and roughness of the floodplain surface, and sediment inputs from tributary streams and other sediment sources). It is, therefore, necessary to assume that the sedimentation rate derived by averaging the mean sedimentation rates for the two transects

Table II. Storage of fine-grained sediment on the channel bed of the study rivers. The values listed represent the mean (with the standard error of the mean in parentheses) of three sampling points located at each site. The values represent the total amount of material resuspended from the channel bed by two different levels of disturbance at the time of sampling (summer 1996) (see text for further explanation)

River	Site	Water agitation (kg m^{-2})	Water and bed agitation (kg m^{-2})	Mean (kg m^{-2})	Organic matter content* (%)	Reach†	Storage (t)
Tweed	a	0·06 (0·02)	0·17 (0·10)	0·12 (0·06)	7	A	322
	b	0·64 (0·27)	1·27 (0·45)	0·96 (0·33)	10	B	1072
	c	0·11 (0·08)	0·14 (0·02)	0·12 (0·05)	11	C	104
	d	0·78 (0·07)	0·93 (0·11)	0·85 (0·06)	13	D	275
	e	0·07 (0·04)	0·56 (0·19)	0·31 (0·09)	7	E	126
	f	0·49 (0·03)	0·78 (0·11)	0·63 (0·05)	9	F	407
	Mean	*0·36*	*0·64*	*0·50*	*10*	*Total*	*2306*
Teviot	g	0·55 (0·13)	1·14 (0·15)	0·85 (0·10)	10	G	561
	h	0·62 (0·38)	1·10 (0·16)	0·86 (0·24)	9	H	1066
	Mean	*0·59*	*1·12*	*0·86*	*10*	*Total*	*1627*
Ettrick	i	0·13 (0·04)	0·20 (0·12)	0·17 (0·05)	6	I	106
	j	0·60 (0·14)	0·94 (0·20)	0·77 (0·05)	4	J	290
	Mean	*0·37*	*0·57*	*0·47*	*5*	*Total*	*396*
All the rivers	***Mean*** ($n = 10$)	***0·41***	***0·72***	***0·56***	***9***	***Total***	***4329***

* Only one sample from each site was analysed for organic matter content
† The length and location of individual reaches were based on the characteristics of the channel bed and the location of tributary streams (see text for further details)

bounding each reach is representative of that reach. The use of an average value is likely to reduce the potential for introducing unrepresentative values of sedimentation rate, but it is suggested that the resulting estimates of sediment deposition for the individual reaches could involve errors of the order of ±20 per cent (based on consideration of the errors and uncertainties associated with the various measurements undertaken). The potential errors associated with the estimates of total sediment deposition for each river and for the Tweed basin as a whole, are, however, likely to be smaller, since errors associated with the values for the individual reaches could be expected to cancel each other out. Nevertheless, a range of ±20 per cent is assumed to represent the potential error associated with the estimate of total floodplain deposition.

Table I presents the estimates of floodplain conveyance loss for each reach of the study rivers. The total conveyance loss associated with the floodplains along the main channels of the three study rivers is estimated to be approximately 44 000 ± 9000 t a^{-1}, with the value for the River Tweed being significantly greater than those for its two main tributaries. When expressed as conveyance loss per unit length of channel, the average values for the rivers Ettrick, Teviot and Tweed are about 280, 140 and 180 t km^{-1} a^{-1}, respectively.

Channel bed storage of fine-grained sediment

Table II presents the results of the measurements of the amount of fine-grained sediment resuspended from the bed of the study rivers. It is assumed that these data provide meaningful estimates of the amount of fine-grained sediment storage on the channel bed at each sampling point. It is important to recognize that no time period can be assigned to the values presented in Table II, which represent an instantaneous estimate of sediment storage at the time of sampling. However, it is likely that channel storage of fine sediment will be at a maximum during prolonged periods of low flow (which occur mainly during the drier summer months in the UK) and that this sediment will be subsequently remobilized during periods of higher flow (in the wetter autumn and winter months) (cf. Adams and Beschta, 1980; Frostick *et al.*, 1984). Since the measurements were undertaken in summer, it is suggested that the values given in Table II represent the annual maximum sediment storage. This storage will be balanced by remobilization at other times of the year, so that for many

areas of the channel bed (cf. Adams and Beschta, 1980) there is no net channel storage at the annual timescale.

As there were no significant patterns in the results of the measurements obtained for the three sampling points at each site, these were averaged (Table II). It is unclear what level of bed agitation best reflects the transient storage of sediment on, and in, the channel bed. However, based on the available empirical evidence (e.g. Beschta and Jackson, 1979; Frostick *et al.*, 1984; Diplas and Parker, 1992) and the D_{50} of the armour layer in the study river (Hey and Thorne, 1986), the estimates provided by the water and bed agitation method (which resuspends fine sediment to depths of approximately 100 mm), are likely to be representative of maximum storage in the active layer (although, locally, fines may infiltrate to depths >100 mm). The water-only agitation method (which resuspends only the fine sediment draped on the surface of the bed) provides a minimum estimate of storage. The average of the values provided by the two methods has been used in subsequent calculations.

There is considerable variability in the resultant estimates of fine sediment storage on the channel bed, and values for individual sites range from 0·12 kg m^{-2} (sites a and c) to 0·96 kg m^{-2} (site b). The mean for all 10 sites is 0·56 kg m^{-2}. The mean organic matter content of the bed sediment is 9 per cent, although values range from 4 per cent (site j) to 13 per cent (site d). It is possible that some of the organic material may represent autochthonous material produced *in situ* on the channel bed, which is, therefore, unrelated to the suspended sediment passing through the system. However, the fact that the organic matter content of suspended sediment samples collected from the study rivers ($n = 23$, mean = 10 per cent) is similar to that for the channel bed sediment suggests that the production of autochthonous organic material on the channel bed is limited.

The values of channel bed storage obtained for the study rivers compare closely to those documented for other rivers in the UK and other areas of the world. Thus, using a similar approach to that adopted in this study, Walling *et al.* (1998a) found that channel bed storage for individual sampling sites within the River Ouse system in Yorkshire, UK, ranged between 0·17 and 9·24 kg m^{-2}, and the mean for all 16 sites was 1·62 kg m^{-2}. Lambert and Walling (1988) estimated that the average amount of sediment released from the channel bed of the River Exe, in Devon, UK, was 0·17 kg m^{-2} using the water agitation method and 0·40 kg m^{-2} using the water and bed agitation method. In a study of surficial fine-grained sediment laminae on the beds of three rivers in southwestern Ontario, Canada, Droppo and Stone (1994) estimated channel bed storage to be in the range 0·66 to 2·20 kg m^{-2}.

The results of fine sediment release presented in Table II may be scaled up to estimate the total amount of sediment stored on the channel bed in each of the study rivers ($S_c(t)$; t) by dividing the rivers into reaches (based on the characteristics of the channel bed and the location of main tributary streams) and assuming that the values of sediment storage obtained for the individual sampling sites are representative of these reaches. That is:

$$S_c(t) = \sum_{i=1}^{n} (R_{bi}(t) W_{br} L_{br} k) \tag{6}$$

where $R_{bi}(t)$ = average sediment release at site i at time t (kg m^{-2}), W_{br} = average width of the channel bed for each reach r (km), L_{br} = length of the channel for each reach (km) and k = a dimensionless scaling factor. The average widths of the channel bed within each reach are based on measurements made at each site by the authors and on measurements of channel width along the study rivers made by the Scottish Environment Protection Agency (D.H.D. McCraw, pers. comm., 1997). The lengths and locations of the channel bed reaches used in Equation 6 are different from those used for the floodplain reaches, first because the two types of site were not always located at the same point, and second, because the first bed sampling site on the River Tweed (site a) is not located at the tidal limit (Figure 2). The resulting estimates of channel bed storage are presented in Table II. The total storage of fine sediment on the beds of the three study rivers at the time of sampling was estimated to be approximately 4300 ± 1300 t. An error band of around ± 30 per cent was obtained using Equation 6 with $R_{bi}(t)$ set to the values for each of the two different agitation methods (i.e. water-only, and water and bed agitation methods) for each site (as opposed to using the mean of the two

agitation methods; see Table II), which can be taken to represent the likely minimum and maximum values of storage at each site under normal flow conditions.

THE FLUVIAL SUSPENDED SEDIMENT BUDGET

It is useful to compare the estimates of floodplain conveyance loss and channel bed storage of fine-grained (less than about 150 μm) sediment obtained for the main channel system of the study rivers with available information on fluvial suspended sediment transport in the Tweed basin. Suspended sediment concentrations and water discharge at the outlets of the Rivers Tweed and Teviot have been monitored since 1994 as part of the LOIS project. However, the final estimates of suspended sediment load for these rivers are not yet available. It is nevertheless possible to estimate the suspended sediment load of the River Tweed at Norham using suspended sediment concentration data collected by the Harmonized Monitoring Programme. These data were combined with the flow record using an interpolation estimation procedure (method 14 of Phillips *et al.*, 1999) and the resulting load estimates were subsequently corrected using the algorithm described by Phillips *et al.* (1999), to compensate for unrepresentative sampling of suspended sediment concentration and discharge. The average sediment load for the River Tweed at Norham for the years 1995 and 1996 estimated using this method is approximately 66 010 t year^{-1} (J.M. Phillips, pers. comm., 1998). This is equivalent to a specific suspended sediment yield of approximately 15 t km^{-2} a^{-1}. The estimated average sediment load is similar to the value of 64 181 t a^{-1} reported by McManus and Duck (1996) for the same gauging site based on calculations involving Harmonized Monitoring Programme data collected during the period 1975 to 1983.

Estimates of sediment conveyance loss and storage can only be directly compared to the suspended sediment flux at the outlet when the degree to which spatial and temporal variability are represented in the various components of the budget has been considered. The estimates of floodplain deposition and channel bed storage presented here are based on a limited number of sites within a drainage basin of about 4390 km^2. Thus, although the data for each site are believed to be representative of a particular reach, the scaling-up of results to the main channel network introduces uncertainty into the final estimates. Despite this, the estimates of conveyance loss and storage presented here are considered to be of the correct order of magnitude. The estimates of floodplain sedimentation are based on ^{137}Cs measurements and represent average values for the last 30 to 40 years. They are 'therefore' likely to be temporally representative. Overbank sedimentation can be considered as medium- to long-term storage (of the order of 10^1 to 10^3 years) in the UK, and thus represent a net conveyance loss at the annual timescale. Locally, channel bank material will be eroded and introduced back into the channel. Although, in the short term, most overbank deposits will be unaffected, it is important to consider sediment remobilization by bank erosion processes when assessing the significance of conveyance losses within the overall suspended sediment budget of the River Tweed. Owens *et al.* (in press) used the fingerprinting approach to estimate that sediment eroded from channel banks contributed an average of about 40 per cent to suspended sediment samples collected from the River Tweed at Norham. A significant, although unknown, proportion of this channel bank-derived sediment would have been eroded from small ditches and from the banks of the numerous streams beyond the main channel network. If, however, it is assumed that 50 per cent of the bank-derived sediment could have been eroded from the banks of the main channel system, then this would equate to an annual remobilization of overbank floodplain deposits of about 13 200 t, which represents only about 30 per cent of the sediment deposited on the floodplain each year. On this basis, it may be concluded that the *net* conveyance loss to floodplain storage at the annual timescale is about 30 800 t a^{-1}.

The estimates of channel bed storage have no temporal base and represent an instantaneous measure of storage at the time of sampling. As already stated, the values of channel bed storage presented in Table II can be seen as representing short-term ($<$1 year) storage (cf. Adams and Beschta, 1980; Frostick *et al.*, 1984), with no net conveyance loss to the fluvial system occurring over an annual timescale. There is also some uncertainty concerning the degree to which the amounts of fine sediment resuspended from the channel bed using the two different levels of agitation represent bed storage, because the depth to which transitory storage occurs within the active layer of the channel bed is unclear. Furthermore, the depth to which fines penetrate and are remobilized from the bed is likely to vary considerably across the width and along the length of the

Table III. Comparison of estimates of floodplain conveyance loss and channel bed storage of fine-grained sediment within the main channels of the study rivers, with the mean annual suspended sediment load for the River Tweed at Norham for the years 1995 and 1996. It is assumed that floodplain storage represents a long-term conveyance loss to the system, while channel bed storage is transitory and does not represent a net conveyance loss to the system at timescales of more than one year

River	Floodplain conveyance loss ($t\ a^{-1}$)	Channel bed storage (t)	Mean annual suspended sediment load ($t\ a^{-1}$)	Total fine-grained sediment delivered to channel system ($t\ a^{-1}$)*	Fine-grained sediment delivery ratio for main channel system (%)
Tweed	26 467	2306			
Teviot	7602	1627			
Ettrick	9851	396			
All three rivers	43 920	4329	66 010	109 930	60

* The total fine-grained sediment delivered to the main channel system is the sum of the suspended sediment load and the floodplain conveyance loss

river. Although this depth is likely to range between 10 and 100 mm in most situations (cf. Beschta and Jackson, 1979; Frostick *et al.*, 1984; Lisle, 1989; Diplas and Parker, 1992), locally it may be considerably greater.

The estimate of suspended sediment load is based on data for the years 1995 and 1996 and is for a different period from that associated with the estimates for the two storage components. In the absence of detailed data on annual sediment fluxes, it is uncertain how representative these two years are of sediment transport conditions over the last 30 to 40 years (i.e. the time period associated with the estimates of floodplain deposition). Furthermore, there are uncertainties and problems associated with the use of infrequent suspended sediment samples to estimate suspended sediment loads (cf. Walling, 1977; Ferguson, 1987; Phillips *et al.*, 1999). Consequently, the estimate of suspended sediment load for the River Tweed presented above must be treated with caution.

Table III presents estimates of channel bed storage and floodplain conveyance losses for the main channel systems of the study rivers, and of suspended sediment load for the River Tweed. Comparison of the estimates of total fine-grained channel bed storage and floodplain conveyance loss for the River Tweed and its two tributaries with the suspended sediment load measured at Norham shows that channel bed storage and floodplain conveyance losses account for about 4 and 40 per cent of the fine-grained sediment delivered to the main channel network, respectively. As the estimates of fine-grained sediment storage and conveyance loss and suspended sediment load relate to different time periods, comparison of these various estimates is to some extent speculative and must be treated with caution. Also, it is stressed that these values relate only to the main channel systems of the rivers Tweed, Teviot and Ettrick Water. The total channel bed storage and floodplain conveyance loss of fine-grained sediment in the Tweed basin as a whole (i.e. for all major and minor tributaries) is likely to be considerably greater.

PERSPECTIVE

Caesium-137 measurements of floodplain sediment cores have been used to estimate average rates of overbank floodplain sedimentation and associated conveyance losses within the Tweed basin over the last 30 to 40 years. Average sedimentation rates for individual transects range from $0{\cdot}16\ kg\ m^{-2}\ a^{-1}$ ($0{\cdot}13\ mm\ a^{-1}$) to $2{\cdot}18\ kg\ m^{-2}\ a^{-1}$ ($2{\cdot}2\ mm\ a^{-1}$) and the mean for all 10 transects is $1{\cdot}29\ kg\ m^{-2}\ a^{-1}$ (about $1{\cdot}3\ mm\ year^{-1}$). The total amount of sediment deposited on the floodplains of the three study rivers averages about 44 000 t a^{-1}. Erosion of channel banks will remobilize overbank floodplain deposits and return about 30 per cent of this sediment to the channel. Consequently, of the order of 70 per cent of the overbank deposits is likely to remain in medium- to long-term storage, and the *net* conveyance loss to the floodplain is estimated to be about 30 800 t a^{-1}. The amount of fine-grained sediment stored on, and in, the channel bed was estimated

using a resuspension technique. Average values for individual sites range from 0·12 to 0·96 kg m^{-2} and the mean for all 10 sites is 0·56 kg m^{-2}. The total amount of fine-grained sediment stored on the channel bed of the main channel system of the three study rivers at the time of sampling was estimated to be about 4300 t. By comparing the estimates of both fine-grained channel bed storage and overbank floodplain deposition with that for the annual suspended sediment load for the River Tweed at Norham, channel bed storage and total floodplain deposition were found to represent about 4 and 40 per cent of the total mass of fine sediment delivered to the main channel system, respectively. These findings indicate that a significant quantity of the fine-grained sediment delivered to the River Tweed and its main tributaries goes into storage. Although the residence time of the sediment stored on the channel bed is relatively short, and is probably less than one year, the residence time of most of the sediment deposited on floodplains during overbank events is likely to be considerably longer.

The magnitudes of the values of channel storage and conveyance loss associated with overbank deposition of fine-grained sediment obtained for the Tweed basin are comparable to those reported for other basins in both the UK and world-wide. In the UK, Walling *et al.* (1998a), for example, using a similar approach to that adopted in the present study, estimated that overbank deposition and channel bed storage along the main channels of the Rivers Ouse and Wharfe, in Yorkshire, represented 39 and 49 per cent, and 10 and 8 per cent, respectively, of the annual suspended sediment load delivered to the main channel system. In the Ouse basin, about 28 per cent of the sediment added to floodplain storage was remobilized by bank erosion. Owens *et al.* (1997) used ^{137}Cs measurements to establish a sediment budget for the Start catchment, UK, and estimated that about 50 per cent of the sediment delivered to the channel system was lost to floodplain storage. Based on an assessment of the fate of Chernobyl-derived radiocaesium, Walling and Quine (1993) estimated that 23 per cent of the total suspended sediment transported through the main channel system of the River Severn, UK, during the period 1986 to 1989, was deposited on the floodplain. Lambert and Walling (1987) measured the suspended sediment load entering and leaving an 11 km reach of the lower River Culm in Devon, UK, where the floodplain was regularly inundated during flood events. They estimated that about 28 per cent of the suspended sediment load was deposited on the floodplain within this reach. The study of Lambert and Walling (1987) and that cited of Middelkoop and Asselman (1994) relate to conveyance losses associated with individual reaches, rather than the entire main channel system. Hence, the total conveyance loss associated with overbank deposition could be expected to be greater than the respective values of 28 and 19 per cent. Estimates of conveyance losses associated primarily with floodplain deposition, obtained by studies in North and South America, range between 10 and 60 per cent of the fine-grained sediment delivered to the channel system or transported out of the basin (e.g. Trimble, 1977, 1983; Meade, 1982, 1994; Roberts and Church, 1986; Phillips, 1991; Kesel *et al.*, 1992; Campo and Desloges, 1994; Mertes, 1994).

Given the uncertainties associated with the various estimation methods used in the studies cited above and the different time periods associated with the resultant estimates of storage and conveyance loss, it is difficult to make any generalizations. However, from the results presented here, and those documented for other drainage basins world-wide, conveyance losses associated with the main channel system appear to range typically between 10 and 60 per cent of the fine sediment delivered to the channel network at the annual timescale.

The routing of fine-grained sediment in most drainage basins is complex. Because sediment storage in basins is both spatially and temporally variable (cf. Trimble, 1993), there are discontinuities in sediment routing and delivery (cf. Church and Slaymaker, 1989), resulting in a 'jerky' sediment delivery system (Ferguson, 1981). Furthermore, this complexity is likely to increase when the fluvial system responds to intrinsic and extrinsic forcing variables (cf. Schumm, 1973; Trimble, 1983; Roberts and Church, 1986), the effects of which may not be detected at downstream gauging stations. Interpretation of sediment fluxes at downstream gauging stations, in terms of upstream sediment mobilization, is fraught with problems and uncertainties. An understanding of the magnitude and residence time of sediment storage and conveyance losses, and how these vary through both time and space within individual drainage basins, is perhaps a more useful indicator of the sediment response of a drainage basin than information on the downstream sediment flux.

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